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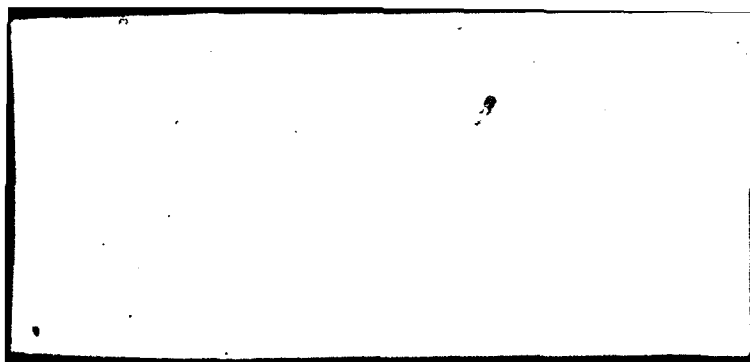| 1.0 | 4.5 3.0 3.5 2.8 | 2.5 |
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MASSACHUSETTS INSTITUTE OF TECHNOLOGY
DEPARTMENT OF AERONAUTICS AND ASTRONAUTICS
EXPERIMENTAL ASTRONOMY LABORATORY ✓
CAMBRIDGE, MASSACHUSETTS 02139

RN-27

PARAMETERS FOR THE EVALUATION OF SONAR DEPTH MEASUREMENT SYSTEMS.

by

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EXPLANATORY NOTE

This is one of a series of Engineering Reports that document
the back-ground studies to be used in a system design for HYSURCH
(Hydrographic Surveying and Charting System). In general, these
reports cover more detail than that finally necessary for a
system design, Any subsystem recommendations contained in these
reports are to be considered tentative. The reports in this series
are.:

RN-22   Soundboat Navigation Equipment and Strategy for
             HYSURCH by John Hovorka

RN-23   The Role of the HYSURCH Survey Ship in the Production
             of Nautical Charts by Edwin A. Olsson

RN-24   An Investigation of Side-Looking Radar and Laser
             Fathometers as HYSURCH Sensors by Jack H. Arabian

RN-25   A Computation Center for Compilation, Revision and
             Presentation of Hydrographic Chart Materials by
             Edwin A. Olsson

RN-27   Parameters for the Evaluation of Sonar Depth
             Measurement Systems by Joel B. Searcy

RN-28   Tidal Measurement, Analysis, and Prediction by
             J. Thomas Egan and Harold L. Jones

RN-29   Applications of Aerial Photography for HYSURCH
             by A.C. Conrod

RN-30   Sounding Equipment Studies, by Leonard S. Wilk

RN-31   Error Analysis of a Dual-Range Navigation Fix
         and Determination of an Optimal Survey Pattern
         by Greg Zacharias

RN-32   Tethered Balloons for Sounding Craft Navigation
         Aids by Lou C. Lothrop

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Office Request for Quotation, N62306-67-R-005.

LIST OF FIGURES

1.0   Introduction

For the benefit of those HYSURCH workers unfamiliar with sonar depth sounders, the following is a brief review of the principals of sonar design and the terminology used to describe sonar systems. The various parameters and figures of merit considered standard in the field of sonar will be defined, and the sonar range equation presented. The ambient acoustic noise environment and the acoustic transmission properties of sea water will be described, and typical data presented for reference.

Once the noise characteristics due to a particular craft are known, they may be combined with the other ambient noise sources, and the sonar range equation may be used to determine the range of operating frequencies which will result in a specified signal to noise ratio.

1.1   Acoustic Depth Measurement

The most common present-day method of depth measurement is by means of underwater acoustical echo ranging on the bottom, sometimes referred to as echo sounding. An echo sounder is a type of sonar, which, by measuring the time difference between the transmission of an electronically generated sound wave and its return after striking the bottom, gives the necessary data for depth determination. In order to achieve an accurate measurement, an average velocity of sound must be determined with respect to the local water temperature and salinity. The device consists of a transducer, either attached to the hull or to a towed vehicle, which serves as both a transmitter and receiver of the acoustical signals. An associated oscillator and amplifiers generate and receive the signals from the transducer. The frequency employed may be anywhere from a few kilocycles to a megacycle or more, the most common region being the low ultrasonic range (20 kc to 30 kc).

In most systems, a pulse-mode transmission is employed, but a continuous transmission, frequency modulation mode (CTFM) is also used. The details of these two types of systems will be discussed in Section 5, after consideration of the general nature of the underwater acoustical environment.

2.0 Velocity of Sound in Sea Water

The basic range accuracy of any sonar system is limited by the precision with which the velocity of sound in water is known. In sea water, the velocity of sound may be expressed as a function of depth, temperature and salinity as[1]

$$c = 4422 + 11.25 \, T - 0.045 \, T^2$$

$$+ 0.0182 \, D + 4.3 \, (S - 34) \tag{1}$$

where

c = the velocity of propagation of sound in sea water in ft/sec.

T = water temperature in $^{\circ}F$

D = depth below the surface in feet

S = salinity in parts per thousand

for nominal conditions, ie. at the surface, for a salinity of 34‰ , and for a temperature of $60^{\circ}F$, the velocity of sound in sea water is 4935 ft/sec. or 1504m/sec. For pure distilled water the velocity of propagation is 1460m/sec. at the same temperature.

Figures 1,2 and 3 illustrate the variation of the velocity of propagation of sound in sea water with temperature, pressure and salinity.
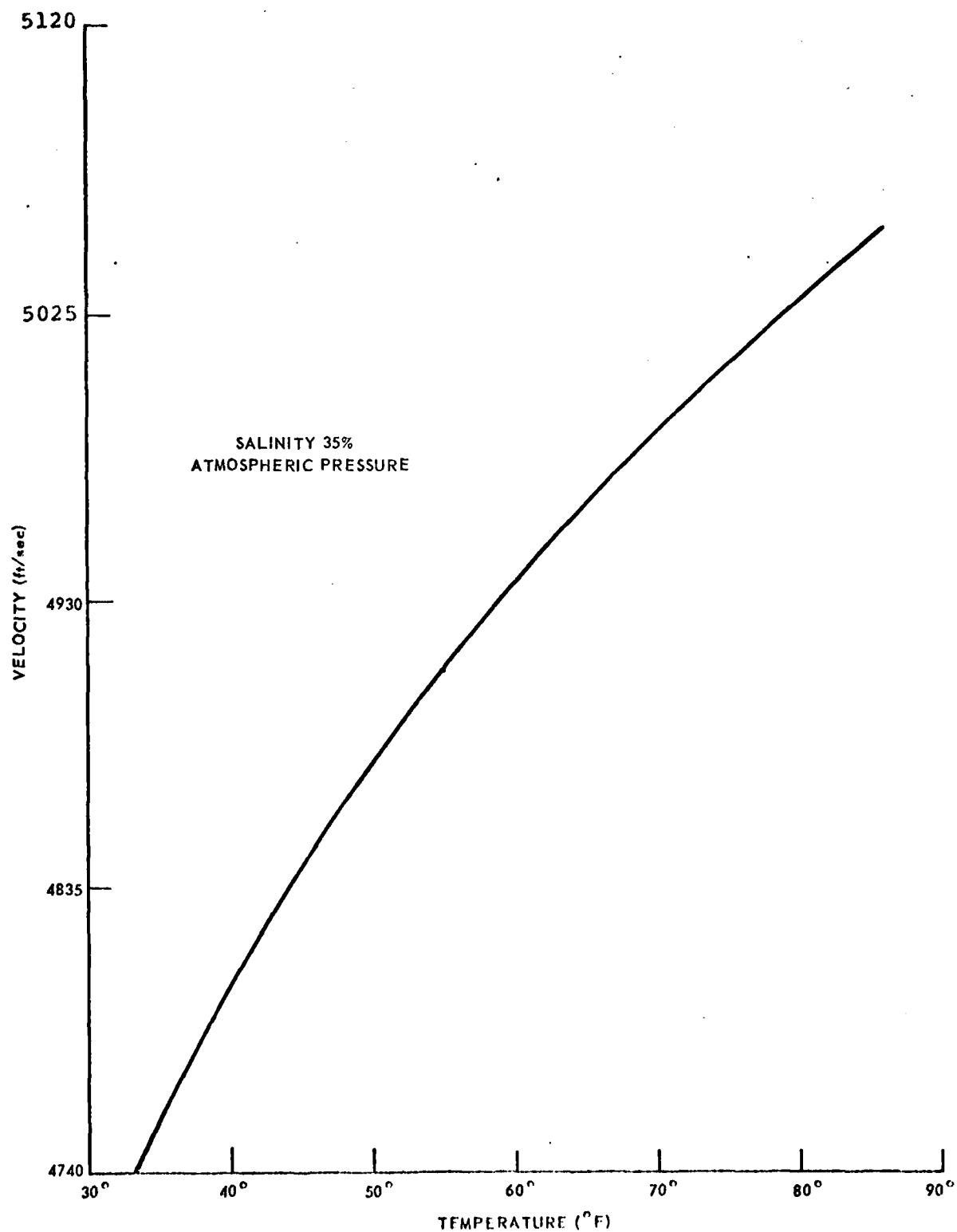
Fig. 1.   The effect of temperature variations on the velocity of sound in seawater.
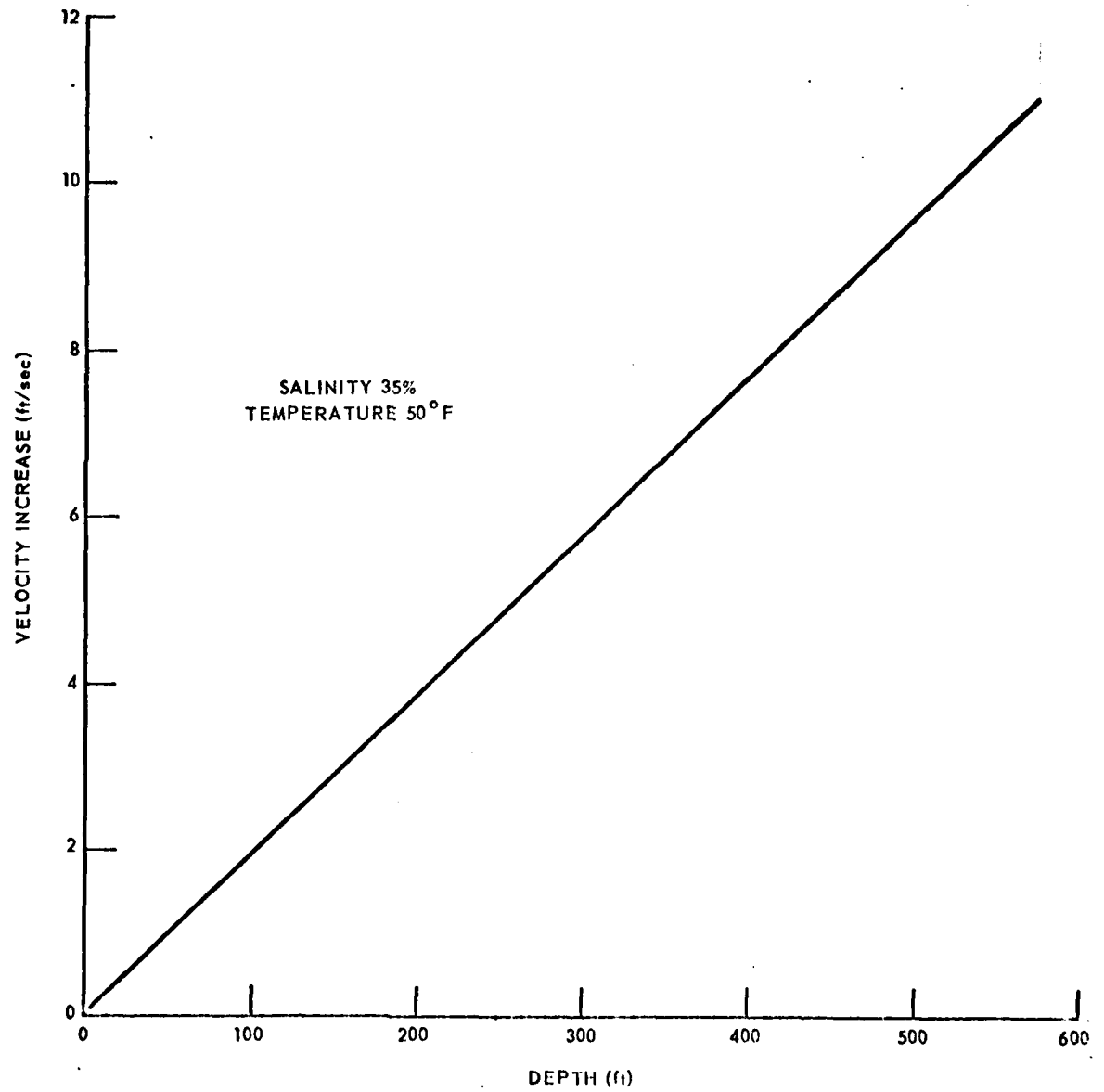
(2)

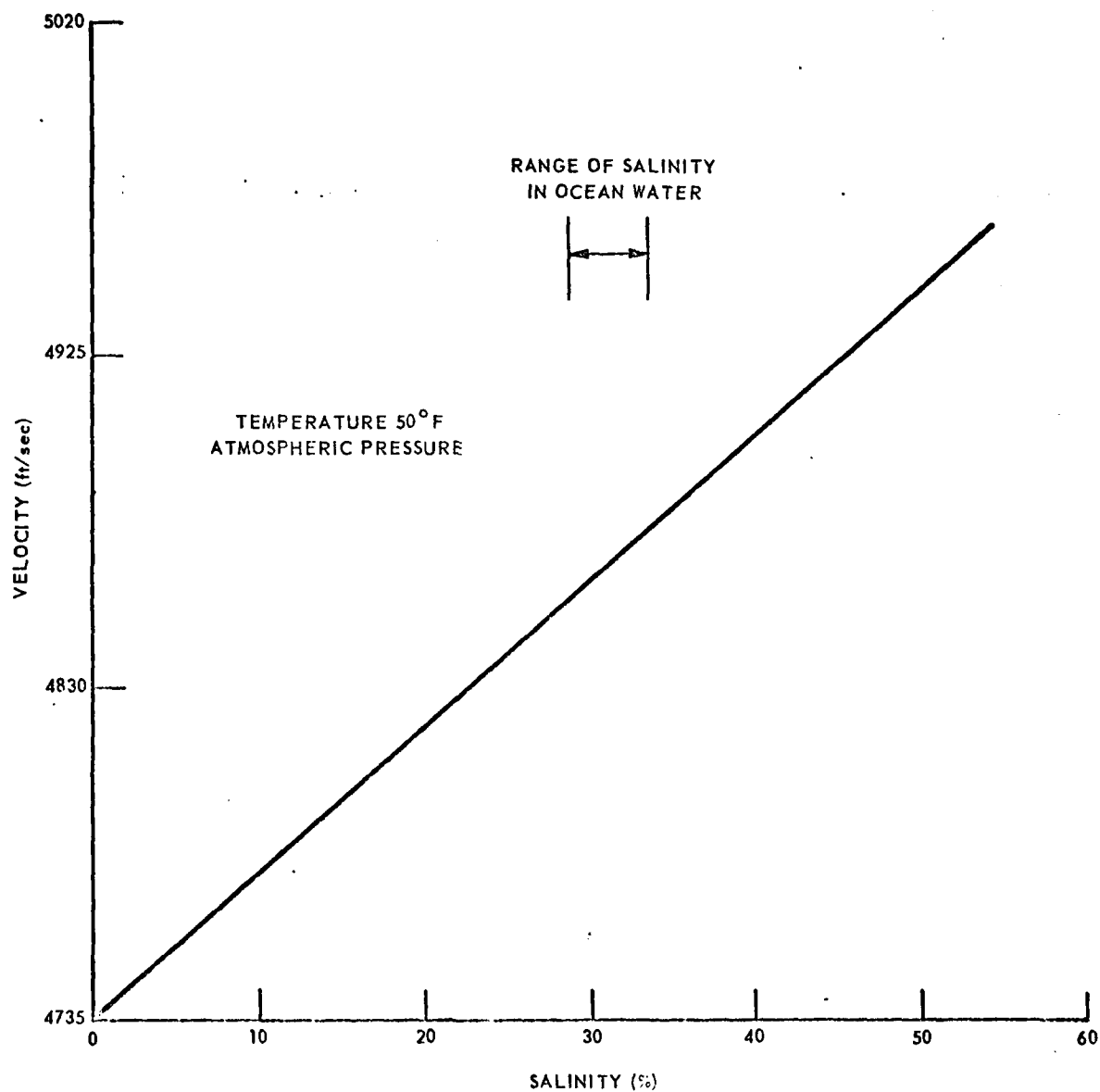Fig. 2. The effect of pressure on the velocity of sound in seawater. [1]

Fig. 3. The effect of salinity on the velocity of sound in seawater.[1]

3.0 Acoustic Intensities and Relative Magnitudes

The intensity of an underwater acoustical signal is measured in units of power per unit area. The signals which may be encountered range in intensity from 10^{-20} watts/cm^2 to 100 watts/cm^2. In view of the size of this range, and in order to emphasize the importance of fractional changes (rather than absolute changes), relative magnitudes are used. Changes in relative magnitude are expressed as ratios, and are given in log units such as the decibel. The reference value to which such relative magnitude ratios are computed must be specified also. This is commonly done by means of notation such as

$$A(db//n_o \text{ watts/cm}^2)$$

which is to be read "an intensity level A db above a reference intensity of n_o watts/cm^2". This then supplies the information on units necessary for the conversion to absolute magnitudes.

4.0 Sonar Transducers

Acoustic transducers for use underwater vary greatly from those used in air. For any underwater transducer to conform properly to its environment, it should operate with about 60 times the force and one sixtieth the displacement, or velocity, of a transducer handling energy at the same rate in air. Underwater transducers must also operate in a high and rapidly changing ambient pressure field.

The most effective means of meeting these requirements is through the use of magnetostrictive and electrostrictive materials. When variations in the strength of a magnetic or electric field take place at acoustic frequencies in these materials, acoustic waves are generated due to the resulting mechanical stress. Conversely, when these materials are subjected to externally applied stress variation such as would be transmitted from an acoustic pressure field in water,

variation in the applied field strength are observed.

The most commonly used magnetostrictive materials are nickel and nickel alloys such as permalloy, nichrome, and monel. The most common electrostrictive transducers are quartz, tourmaline, Rochelle salt, and barium titanate.

5.0   Sonar Depth Measurement Systems

5.1   Vertical Beam Sonar Echo Sounders

The most elementary and widely used acoustical depth measurement technique is vertical beam sonar. In this configuration, the transducer is mounted on the survey craft hull or towed in a "fish" so that the main transmitted beam is directed downward. The time to the first returning echo then measures the range to the nearest point on the portion of the bottom insonified. The transmitted acoustic energy may be in the form of either a series of pulses or a continuous frequency modulated wave. In pulse mode systems, the pulse repetition frequency is limited by the maximum range to be measured by the relative

$$(prf)_{max} = \frac{c}{2R_{max}} \tag{2}$$

where R_{max} is the maximum range (depth) expected and c is the velocity of sound in sea water.

A continuous transmission frequency modulated (CTFM) system transmits a linear ramp of frequency with time and measures continuously the frequency difference between transmitted and return signals (see Figure 4). Since the rate of change of frequency with time, df/dt is a known constant, the round trip time interval Δt can be determined from the relationship

ROUND TRIP TIME FOR SIGNAL $= \dfrac{2D}{C}$
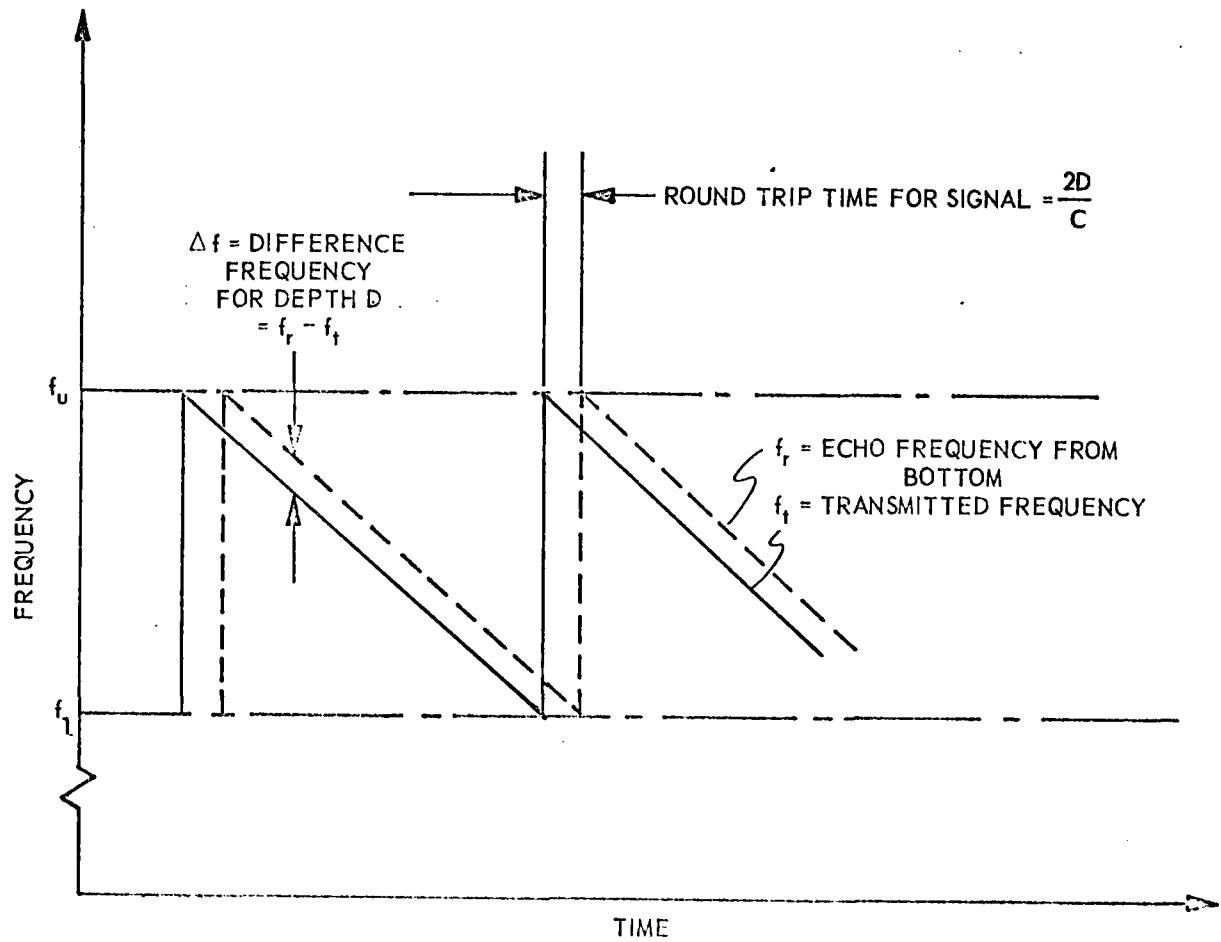
Δf = DIFFERENCE FREQUENCY FOR DEPTH D $= f_r - f_t$

f_u

f_r = ECHO FREQUENCY FROM BOTTOM
f_t = TRANSMITTED FREQUENCY

FREQUENCY

f_l

TIME

Fig. 4. Frequency vs. time for a typical CTFM sonar depthfinder.[4]

$$\Delta t \ \frac{df}{dt} \ = \ \Delta f \qquad\qquad (3)$$

and range to the bottom is obtained as with the pulse system, from the range equation

$$R = \frac{c \ \Delta \ t}{2} \qquad\qquad (4)$$

A CTFM sonar depth profile has been operated satisfactorily at 29 knots while mounted on a hydrofoil[2].

5.2   Side-Looking Systems

There are two basic types of side-looking sonar systems. The most common type uses a fan shaped beam very narrow in the fore-aft direction and directed abeam. Pulses are transmitted and the return is displayed as a function of time along a line. Successive pulses build up a "picture" of the bottom abeam. Since the return is displayed against time rather than angle however, only slant range to acoustically irregular features on the bottom is available. Such a system is primarily useful for obtaining qualitative information or obsticle detection abeam, and might serve as an "acoustic wire drag"[3].

A seond type of side looking sonar is made up of one or more narrow beam transducers arranged to look abeam. In such a system, true depth at the insonified point can be computed provided the orientation of the beam (or beams) relative to the vertical is known. A system of this type is the phased array aboard the Silas Bent.

The remaining secitons of this report will be devoted to a presentation of the parameters and figures of merit used to characterized performance in any type of sonar echo ranging system.

6.0   Ambient Acoustic Noise in the Sea

The ambient acoustic environment in the sea is, in
general, due to a number of sound sources. These sources may
be grouped into three broad catagories; (1) noise due to
water motion, (2) marine life noises, and (3) man-made noises.
The general character of the noise to be expected from each
of these sources will now be examined.

6.1   Noise Due to Water Motion

The motion of the water itself can generate acoustic
noise in a number of ways. Surf breaking on a reef or shore
may be detected for several miles. In shallow water, tidal
currents may cause small stones or pebbles on thebottom to
move sufficiently to create considerable sound. Waves cresting
and breaking in open water, and the escape of air bubbles
trapped as a result of wave aciton also create water noise.

Water noise varies greatly with time, location and
weather, and considerable statistical averaging is necessary
to arrive at representative data. Figure (5) shows some
typical water noises spectrum levels for sea states 0 to 5.
The curve labeled minimum water noise represents the level
of noise that might be expected in deep open ocean water,
and represents the minimum level that might be encountered
in practice. The "thermal limit" shown on the figure represents
the limit beyond which it is impossible to measure acoustic
energy in water using an ideal hydrophone at $60^{\circ}F$ water tempera-
ture.

A further indication of the effects of wind and wave
action on water noise is given in Figures (6) and (7). Here,
the statistical average of the band level of noise in the 0.1
to 10 KC band is plotted for various wind velocities and wave
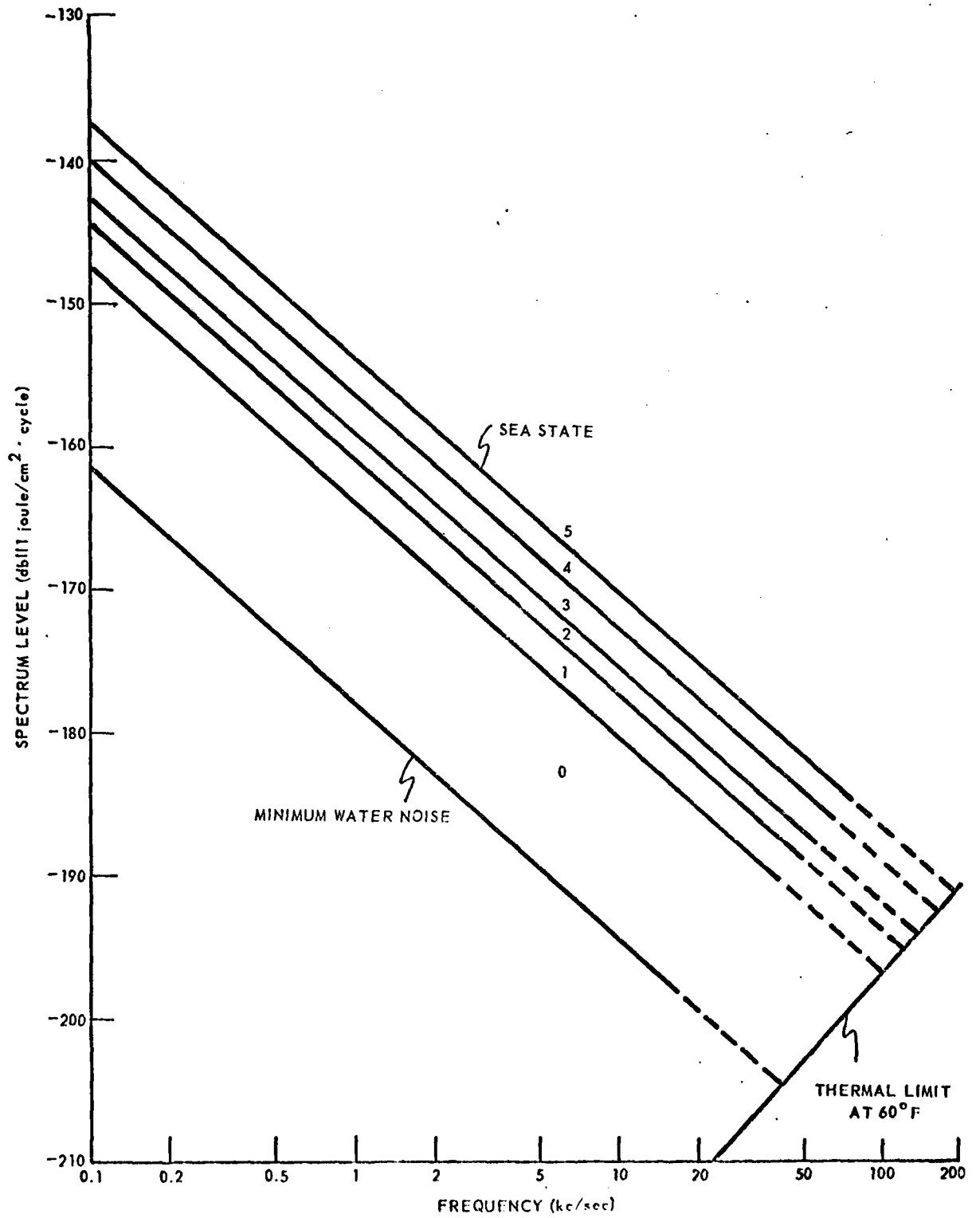heights.

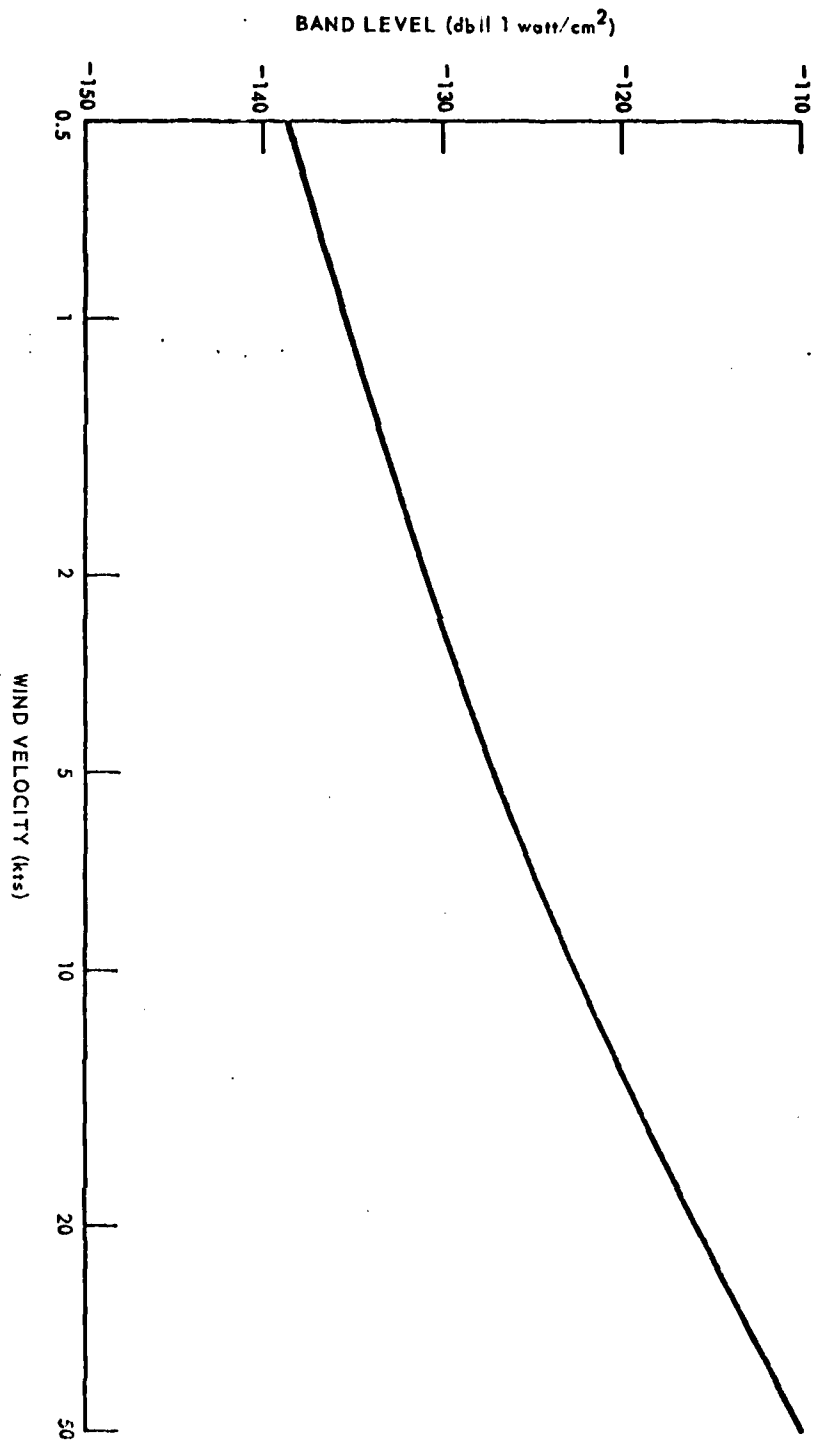Fig. 5. Spectrum levels of water noise for various sea states.[1]

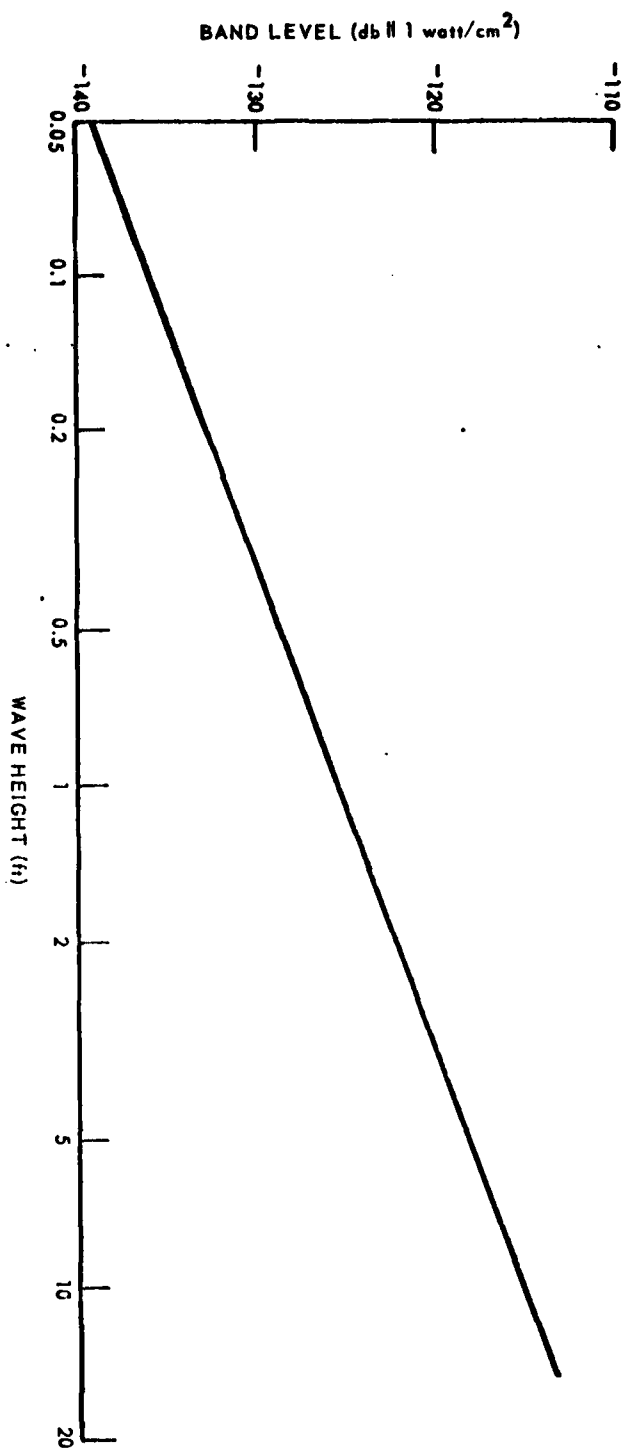Fig. 6. Effect of wind velocity on water noise in the 0.1 to 10 kc band.

Fig. 7. Effect of wave height on water noise in the 0.1 to 10 kc band.

The noise due to movement of bottom materials is so diverse that it is impossible to even attempt a statistical representation of this effect.

6.2   Noise Due to Marine Life

Several forms of marine life create sonic disturbances, the most notable of these being croakers (a variety of drumfish) and snapping shrimp. The spectrum levels of the resulting noise varies greatly with location and time of day, but representative levels are shown in Figure (8).

6.3   Man-Made Noise

Many sounds existing in the ocean are of man made origin, the most common of these being ship noises. In harbors or industrial areas, a wide variety of noise sources might be present. Two typical spectra from these areas are shown in Figure (9). The general spectral shape of ship traffic noise does not differ greatly from general water noise although in practice it may exhibit more pronounced peaks.

The spectrum of noise due to a single ship is a function of hull type, speed and displacement. The variation of the noise spectrum with speed for a large cruiser is illustrated in Figure (10). In general it has been observed that the spectrum is relatively smooth for normal and high operating speeds, displaying a comparatively straight characteristics for frequencies above 1 kc/sec. The slope of this straight portion decreases with increasing speed, indicating the expected emphasis of higher speeds. Below 1 kc/sec, the spectrum begins to curve downward with decreasing frequency in such a way that it passes through a maximum between 100 and 500 cps. Low frequency peaks due to cavitation frequently fall in this same region.
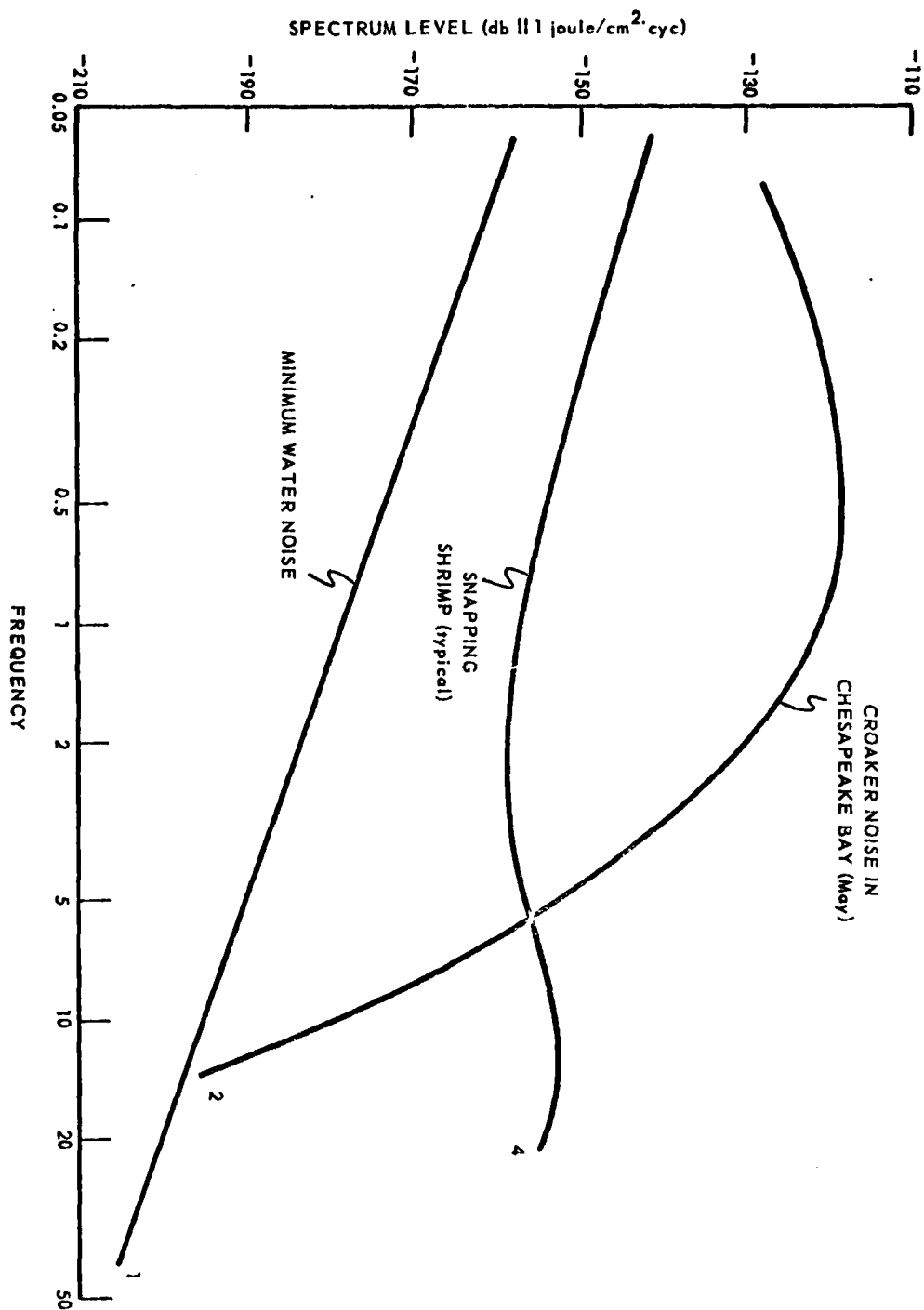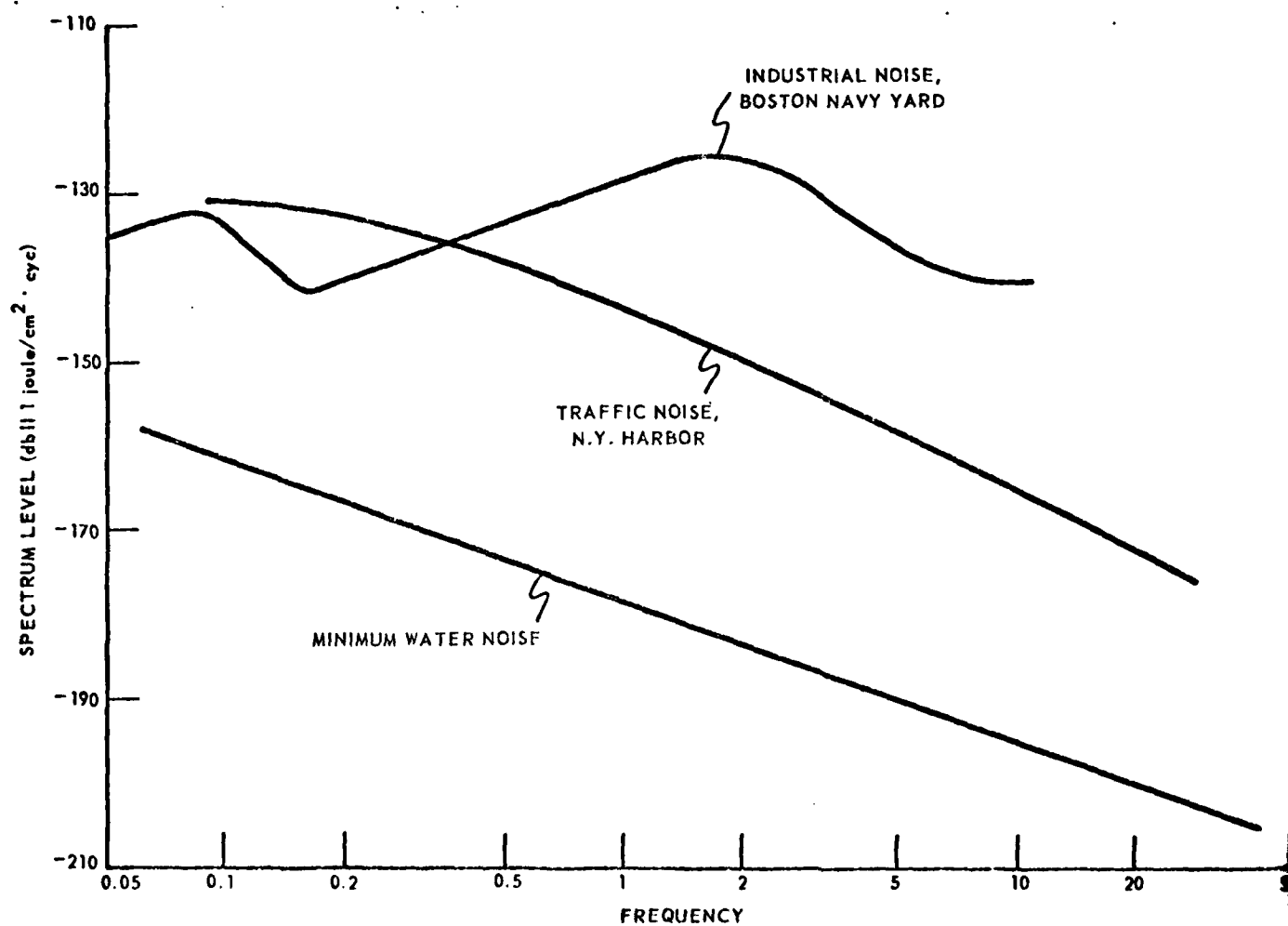
Fig. 8. Typical noise spectra due to marine life. [1]
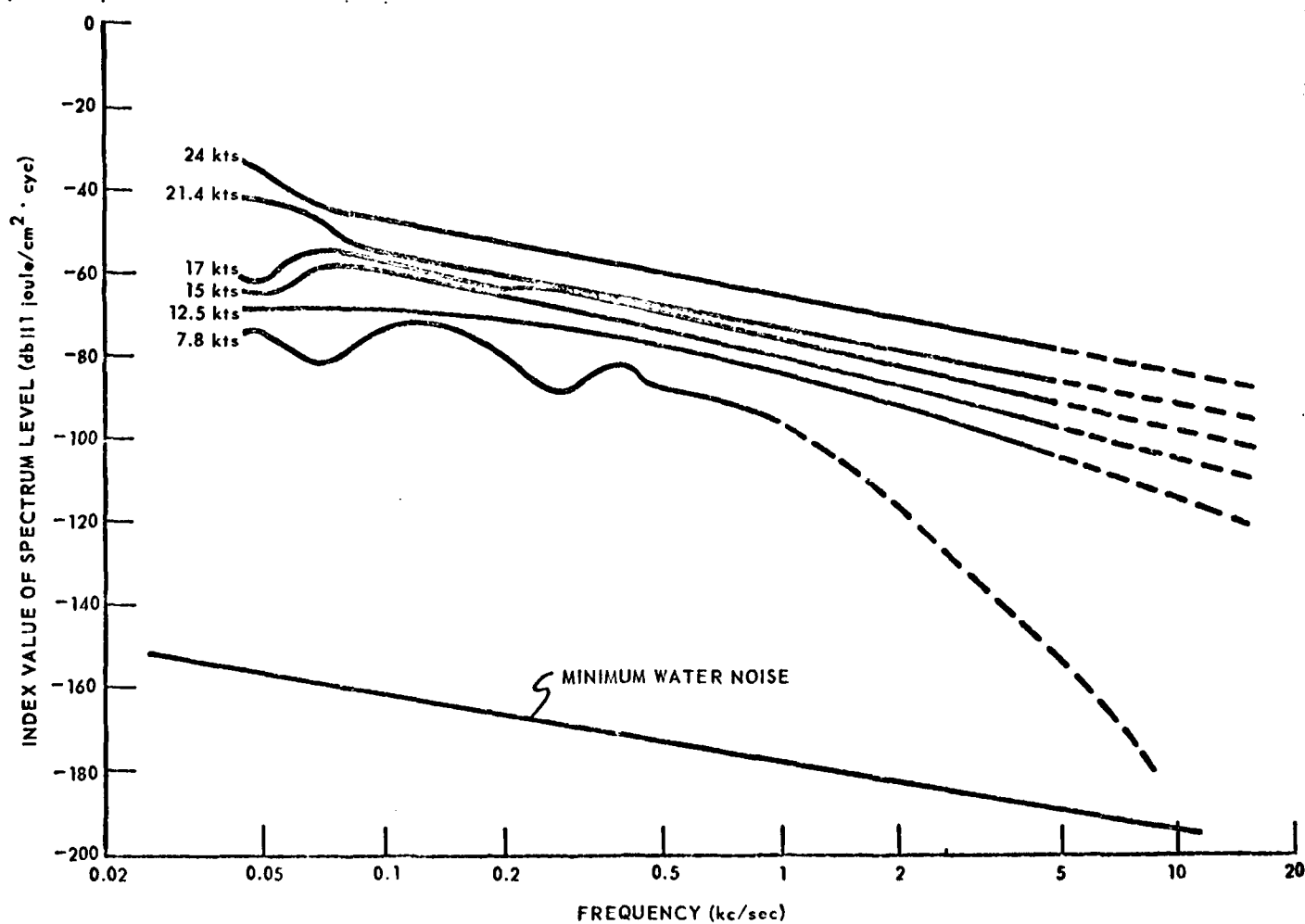
Fig. 9. Typical harbor noise spectra.(1)

Fig. 10. Spectrum levels of acoustic noise due to a large cruiser.[1]

Figure (11) illustrates the variation of the index value of the spectrum at 5 kc/sec with velocity for a ship of 400 tons displacement.

The above data are presented as typical of large ships, and are not readily extrapolated downward to smaller ships.

6.4   Addition of Acoustical Levels

It is frequently necessary to determine the total acoutical transmission level of some sound which is known to be composed of two component sounds. If the intensities I_1 and I_2 of the component sounds are known, the level difference between the two sounds is

$$\Delta L = L_2 - L_1 = \lg t \left(\frac{L_2}{I_1} \right) \tag{5}$$

where $\lg t\ R = 10 \log_{10} R$.

The level difference between sounds having intensities $I_1 + I_2$ and I_1 is

$$L_{sum} - L_1 = \lg t \left(\frac{I_1 + I_2}{I_1} \right) = \lg t \left(1 + \frac{I_2}{I_1} \right) \tag{6}$$

Since these two level differences are both functions of the intensity ratio I_2/I_1 alone, they are unique functions of each other. Figure (12) shows the result of plotting values of $L_2 - L_1$ for corresponding values of $L_{sum} - L_1$. This plot then allows the determination of the acoustical level L_{sum} due to two sound sources which, if present alone would have levels L_1 and L_2. This is parituclarly useful in connection with the separate noise source characteristics given in this section.
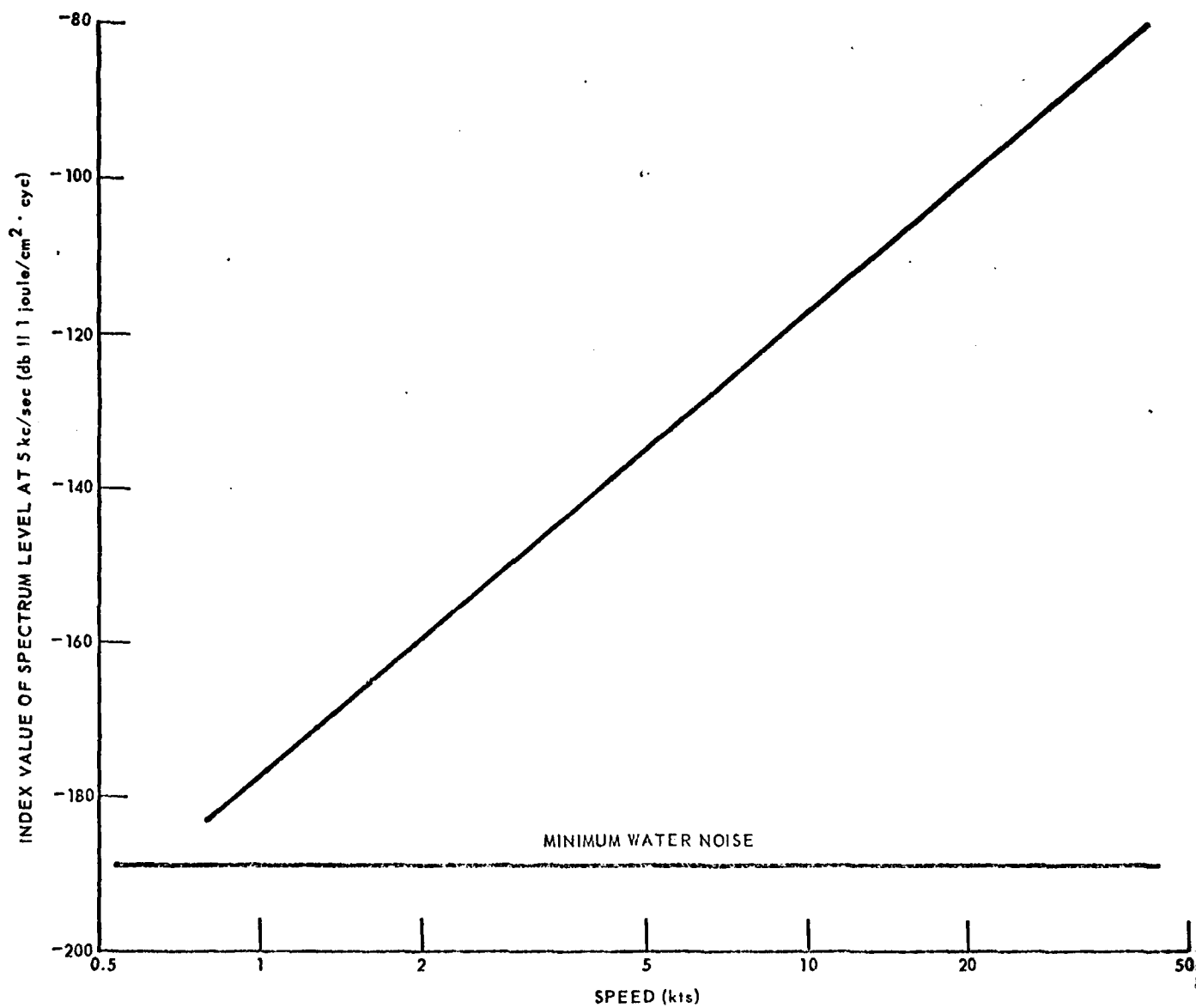
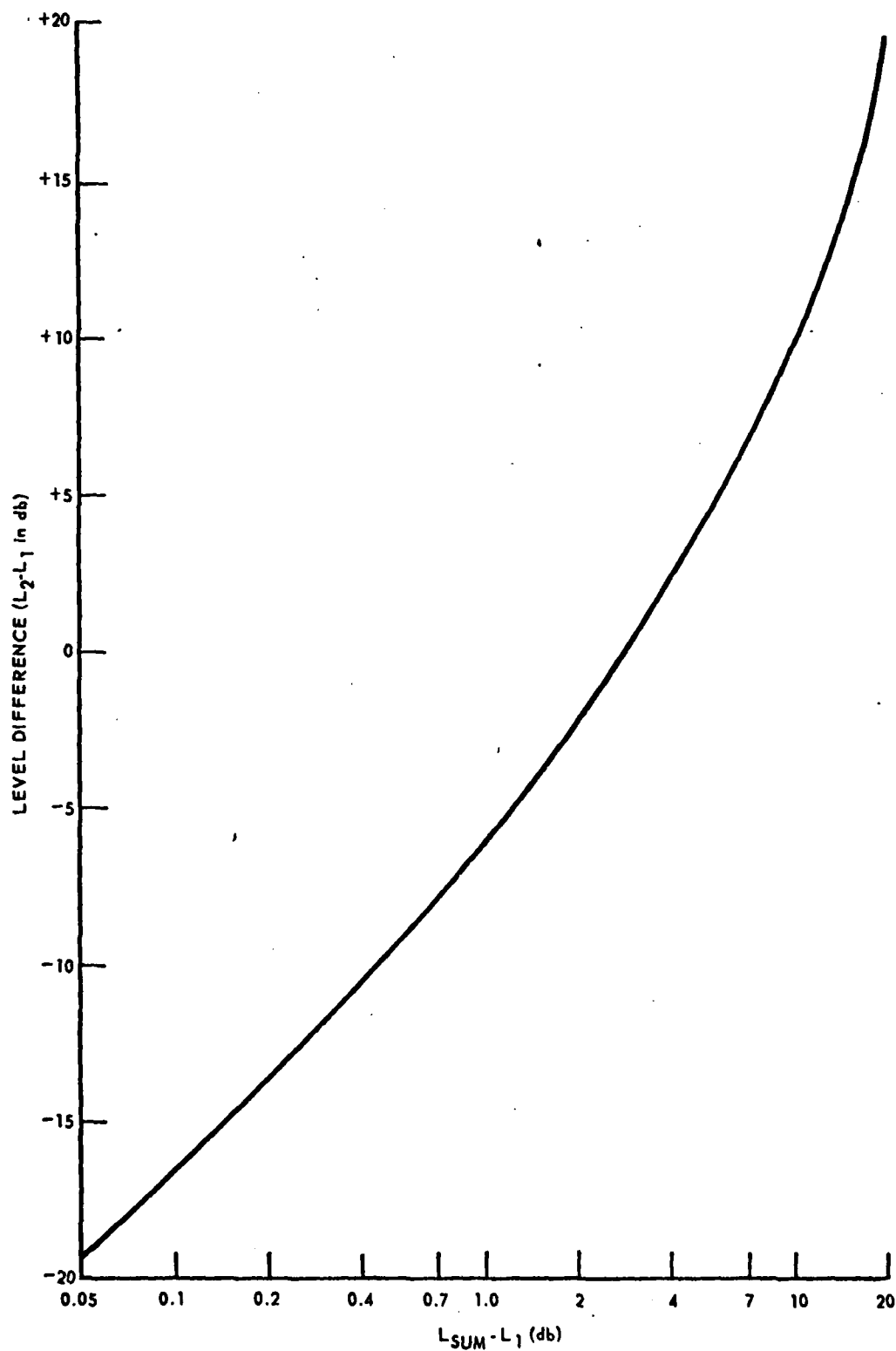Fig. 11. Effect of speed on ship sounds (typical of ships of 400 tons).[1]

Fig. 12. The addition of acoustical levels.[1]

7.0   Parameters and Figures of Merit for Sonar System

In order to evaluate the performance of a sonar system, we must first define several parameters and figures of merit which will enter into the basic sonar range equation. The most commonly used of the terms are defined below.

7.1   Propagation Loss

Sound energy propagation in sea water is subject to two classes of propagation loss. The first of these is called spreading loss, and for ranges less than a few hundred yards follows the inverse square law. At greater ranges, refraction and reflection of the wavefront cause departure from the inverse square law loss.

The second basic class of propagation loss is attenuation loss, and is due to the combined effects of scattering and absorption.

The relative contribution of spreading and attentuation losses to the total propagation loss, N_w , as a function of range is shown in Figure (13). Note that spreading loss predominates out to ranges of several hundred yards, thus would be the dominant mode of loss in shallow water acoustical depth sounders.

Attentuation loss is a function of the frequency of the acoustic signal. The attenuation coefficient in sea water is plotted as a function of frequency in Figure (14).

7.2   Source Level

The level of the acoustic pressure in the water produced by a given driving power to the transducer is referred to as the sonar level. The pressure is generally given in db relative to a reference level such as 1 dyne/cm^2 at 1 yard. Source level may then be written
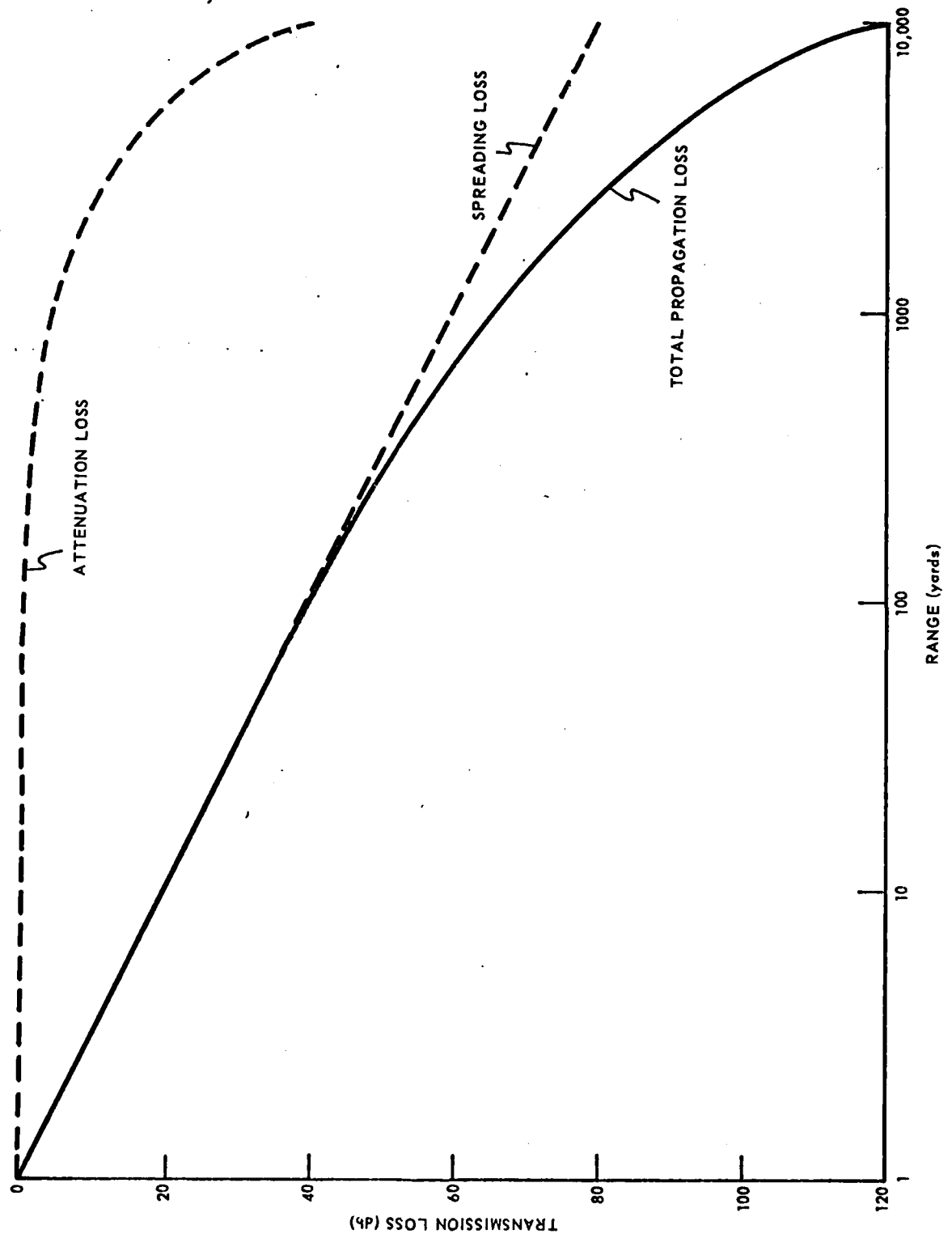
$$L_s = TR/W + 10 \log_{10} P_{in} \qquad (7)$$

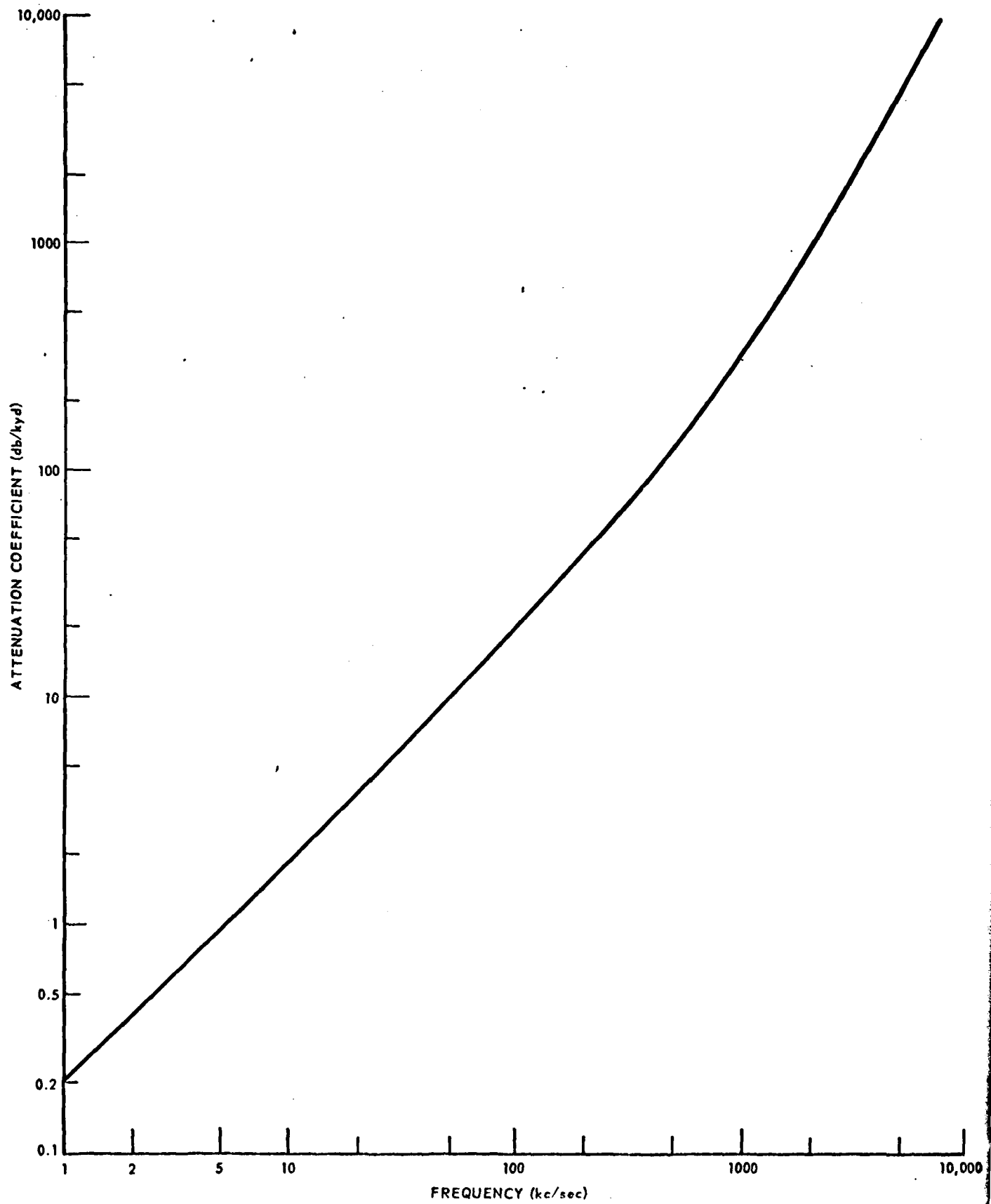Fig. 13. The components of propagation loss as a function of range.[1]

Fig. 14. Nominal acoustic attenuation coefficient in water.[1]

Where L_s and TR/W are source level and transmitting response per watt in db referenced to 1 dyne/cm^2 at 1 yard, and P_{in} is the transducer input power in watts. The transmitting response per watt is a transducer characteristic expressing (in db) the efficiency of the transducer in converting electrical power to acoustic power.

7.3   <u>Directivity Factor and Directivity Index</u>

The directivity factor is a figure of merit used to express the effect of the directional properties of a transducer on its overall operational performance. The transmitting directivity factor is defined as the ratio of the acoustic power radiated over all bearings by the transducer when excited by a given sinusoidal frequency and power to the acoustic power which would be radiated over the same bearings if the response of the transducer were the same for all bearings as for the bearing of maximum response. The receiving directivity factor is similarly defined and is generally numerically equal to the transmitting directivity index.

The directivity factor is therefore measured by the ratio of two rates of energy flow and describes a property of an energy transmission system which, like its efficiency, determines the effectiveness with which the system transmits or receives energy in a specified direction. The property thus described may then be described in terms of a transmission loss.

The transmission loss measured by the directivity factor of a sonar transducer is known as its directivity index, and is defined as

$$N_{DI} = 10 \log_{10} \frac{1}{\text{directivity factor}} \qquad (8)$$

Typical directivity index values for a circular plate transducer and a line transducer as a function of 3 db beam width are shown in Figure (15).
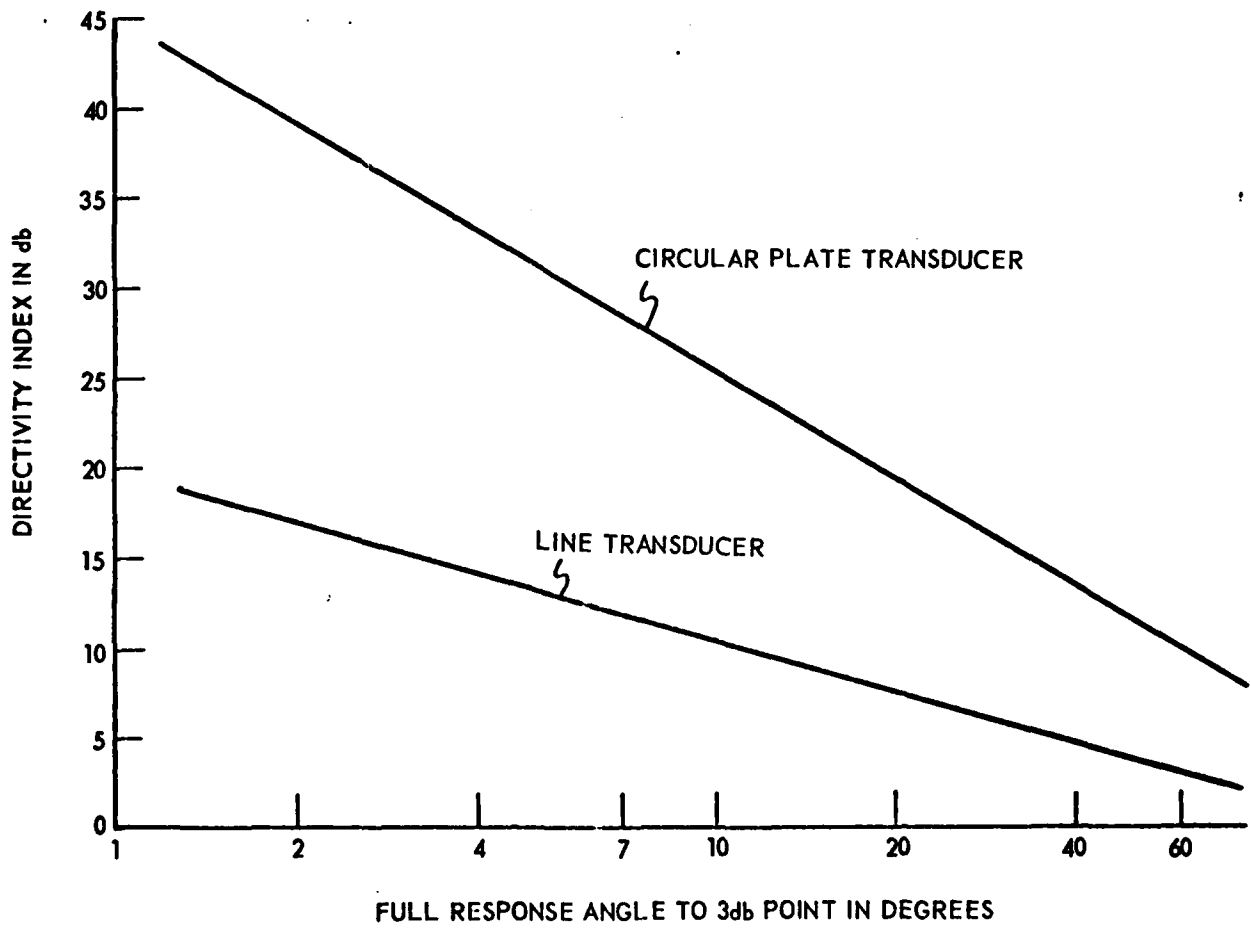
FULL RESPONSE ANGLE TO 3db POINT IN DEGREES

Fig. 15. Directivity index as a function of 3db beam width

7.4 Recognition Differential

As the magnitude of a received signal decreases relative
to the noise present, the reliability with which the signal
may be detected decreases. The reliability of an observa-
tion made at a given signal to noise ratio may be expressed
in terms of the probability of detecting the signal. Figure
(16) shows the variation in this probability with signal to
noise ratio in db. The value, in db, of the signal to noise
ratio characteristic of a specified observational probability
is designated as the recognition differential, N_{RD}.

7.5 Target Strength

Target strength is a figure of merit used to describe
that component of transmission loss due to target reflectivity,
dimensions, and geometry. It is usually a measured character-
istic of various targets, determined by the difference between
measured two-way transmission loss and echo loss. In the case
of echo sounding however, the target, the bottom, can be at
least approximately modeled.

Target strength can be defined as the diffenence between
the level of the echo corresponding to a target range of one
yard and the level of the outgoing acoustic pulse. In the case
where the target is a large plane surface, it has been shown
(1) that the target strength is given by

$$N_{TS} = 20 \log_{10} R - 6 \text{ db} \qquad (9)$$

where R is the range to the target plan in yards. In the
case of a depth sounder, the range R would be replaced by the
depth in the case of a vertical beam sonar, or by slant range
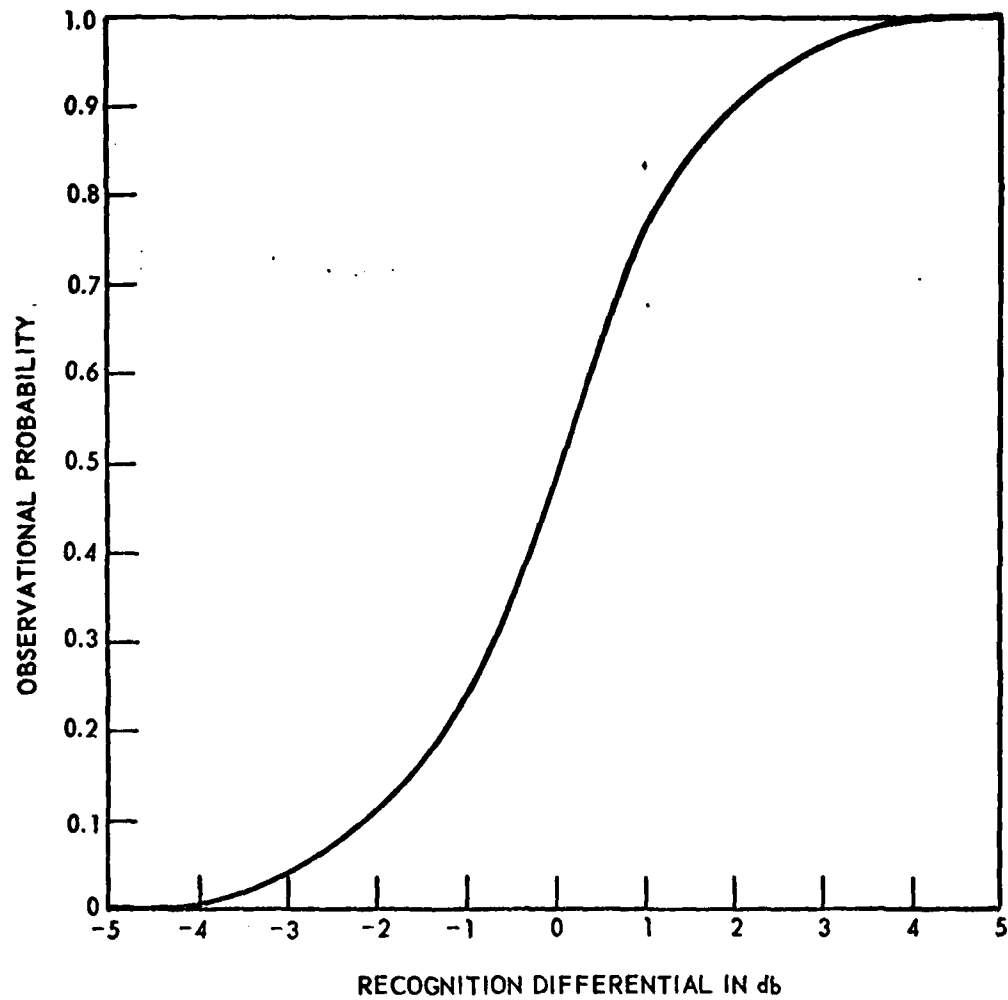in the case of a side looking sonar.

Fig. 16. Recognition differential as a function of the probability of correctly detecting the signal.

8.0 The Sonar Echo Ranging Equation

Using the variables and figures of merit described above, we may now write the sonar echo ranging equation as

$$N_{RD} = L_s + N_{TS} + N_{DI} - L_n - 2N_w \qquad (10)$$

where

N_{RD} = the recognition differential, db.

L_s = the source level in db//1 dyne/cm^2 at 1 yard.

N_{TS} = the target strength, db.

N_{DI} = the directivity index, db

L_n = the local noise level in the frequency passband of the receiver in db//1 dyne/cm^2 at 1 yard.

N_w = the one-way*propagation loss between the transducer and the target, db.

The equation may now be used to evaluate the maximum range at which the recognition differential has a minimum acceptable value with a given system, or to trade off system parameters such as transducer power, response and geometry against maximum range and recognition differential.

9.0 Conclusion Regarding Shallow Water Sounding

Since a shallow water spreading loss predominates over attenuation loss, we are generally free to choose the higher operating frequencies without significant penalty. The spectra of the interfering noise sources were seen to fall off steadily toward these higher frequencies, thus we would expect

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* Note that the round trip propagation loss is twice the one-way loss rather than the loss associated with the round trip range due to the facet that the target acts as a secondary emitter of acoustic waves.

that for a given transducer power and range, that the signal
to noise ratio would inprove as the operating frequency is
increased, until attenuation loss begins to predominate.
For a given interfering noise spectrum, the optimum operating
frequency may be determined by plotting equation (10) as a
function of frequency for a given maximum range and transmit-
ted power. The resulting curve will exhibit a peak at the
frequency for which the signal to noise ratio is a maximum .
In general, rather than determining the optimum frequency
this procedure determine the band of operating frequencies
over which the recoginition differential, and thus the signal
to noise ratio, is above some minimum acceptable value.

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